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ON LOCATING JET STREAMS FROM TIROS PHOTOGRAPHS

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ABSTRACT

The purpose of this study is to evaluate the reliability of locating jet streams by means of certain cloud patterns in TIROS pictures, and to determine the most definitive characteristics of those patterns. It would be very useful operationally, especially in data-sparse regions, if the jet stream could be accurately located from satellite pictures.

Jet stream positions over the United States estimated from TIROS pictures are compared with positions from operational analyses during a 3-month period. Initially agreement is achieved in about half the cases. The cases are re-examined to determine under which conditions agreement did or did not occur.

Jet streams can be accurately located in about 80 percent of the cases whenever clearly defined cloud characteristics occur under favorable viewing conditions. The most definitive cloud characteristics are (1) an extensive cirrus shield having a sharply defined poleward edge, often outlined by a shadow cast on lower cloud surfaces or on the earth, and (2) transverse banding in the cloud shield. The jet axis is located on the poleward cloud edge. Further, cirrus streaks alone prove to be undependable detectors. The greatest danger exists in confusing frontal cloudiness with jet stream cloudiness. There is the suggestion that operational jet analysis can benefit from satellite pictures even in data-rich areas.

1. INTRODUCTION

Evidence that cirriform clouds associated with the jet stream may sometimes be detected in satellite photographs has been presented by several authors: Lester, Hall, and Thompson [10], Conover [4], and more recently Oliver, Anderson, and Ferguson [14]. They found that cirriform clouds are largely restricted to the anticyclonic shear side (tropical side) of the jet stream and are characterized by an abrupt edge along the jet core. The type described by Lester et al. and by Conover were largely cirrus streaks and bands whereas the type discussed by Oliver et al. were extensive cloud shields or layers.

The latter authors pointed out that a shadow cast on underlying clouds or the earth may enhance the definition of the cirrus cloud edge. Further they suggested that pictures showing these cloud characteristics might be used to identify and position the jet stream. If so, the satellite should be a powerful tool in sparse data areas, a more powerful tool than either ground or aircraft cloud observations. A satellite view is many times broader, and observations of cirrus are not hampered by intervening clouds.

The study attempts to evaluate the reliability of the hypothesis that certain cirrus cloud characteristics in satellite photographs can be used to locate accurately the jet stream; and further to determine the most definitive characteristics of these cloud patterns.

2. BACKGROUND

A great variety of jet stream cloud forms have been suggested, not only among the aforementioned authors using TIROS pictures, but also elsewhere in the literature. Kadlec [9] suggested that the cirrus is essentially an overcast layer of cirrostratus. Similarly Sawyer and Ilett [15] and Murray [12] found the cirrus to be predominantly layered. Conover [3] recognized the possibility of both jet-associated cirrus sheets and streaks or bands; although later, when presenting TIROS views, Conover [4] seemed to emphasize the streaked or narrow banded nature of the cirrus. Long, narrow streaks and bands a very few miles wide have been used by Frost [6, 7] to locate and fly in the jet stream. Schaefer [16] has noted that jet-associated high and middle clouds appear in a variety of forms to the ground observer.

He too has noted the streaked nature of cirrus, which he describes as "long tufted streamers" and "complex shear lines." In addition, he has described cirrus appearing in "massive whorls" and cirrocumulus in "blanket-like masses . . . sometimes in a line." Clouds of this latter type may appear in the satellite television pictures as patches rather than streaks, bands, or layers.

In addition to the appearance of the clouds, there is the question of jet stream position relative to the clouds. Neither theoretical nor observational studies have been conclusive about this point. It must be remembered, however, that the observational studies were hampered by the ambiguities resulting from the sparsity and inaccuracy of upper-air data, and that those using cloud observations from the ground or aircraft were further hampered by a limited view.

A theoretical model originally proposed by Riehl et al. [19], and later discussed by Beebe and Bates [1], relating to the dynamics of the jet stream in the area of a wind speed maximum, aids in analyzing the relationship of jet streams to high-level clouds. In this model horizontal divergence is required on the tropical side of the jet stream in the entrance area and on the polar side in the exit area through the mechanism of positive vorticity advection. Conversely, convergence is required in the remaining areas of the wind speed maximum. Of course, curvature in the jet stream could alter this divergence pattern. It can be argued that the immediate proximity of the tropopause above the jet stream serves as a boundary or lid so that the divergent areas around the jet stream generate upward motion immediately below the jet stream. Or it can be argued that the horizontal divergence is strongest at the jet level, so that the decrease of divergence downward in the layers below permits upward motion. At any rate divergence at the level of the jet stream favors ascent in layers immediately below the jet stream level.

This model is consistent with the work of Murray and Daniels [13], who found upward motion in the tropical entrance area and the polar exit area of the jet stream maximum. Also, evidence that cirrus is more frequently observed in areas of positive vorticity advection has been presented by James [8] and by Bundgaard [2]. From this it seems that clouds may be as likely on the polar side in the exit area of the jet stream as in the tropical entrance area, assuming adequate moisture is available on the cold (polar) side. Murray [12] and Vuorela [21] have provided evidence of drier air on the polar side of the jet stream than on the equatorward side at the same level. Although the work of Sawyer and Ilett [15], Murray [12], James [8], and McLean [11] indicates cirrus is not unusual on the polar side of the jet stream, they seem to agree, with the possible exception of McLean, that the clouds are more frequent and extensive on the tropical side of the jet stream. Also there is general agreement that the clouds are lower on the cold side and occur below the usually lower tropopause there. The general concept of extensive clouds on the tropical side of the jet stream is supported by Schaefer and Hubert [17], Kadlec [9], and Oliver, Anderson, and Ferguson [14]. The latter two studies do provide for exceptions in the case of two closely spaced jet streams but this will be discussed later.

Whether clouds appear on both sides or not, there is evidence by Murray [12] and the implication by McLean [11] that a break occurs in the immediate vicinity of the jet stream. From aircraft penetrations in a number of jet streams, Endlich and McLean [5] found an average downward motion of 40 cm. sec.$^{-1}$ in the zone immediately poleward of the jet stream.

3. EVALUATION PROCEDURE

Simply, the general procedure was to locate probable jet stream positions geographically using only TIROS photographs with their grids and nephanalyses, then compare these positions with those from operational jet stream analyses.

Because of its relatively dense network of upper-air data, the United States was selected as the area of study. The period of study chosen was a cold season, when the greatest frequency and intensity of jet streams are expected. Three factors led to the selection of the period November 1962 through January 1963: (1) the excellent satellite coverage provided by the simultaneous operation of TIROS V and VI, (2) the superior picture quality of these satellites compared with TIROS I–IV, and (3) the occurrence of this period before jet stream interpretations were entered on the operational nephanalyses, thereby removing possible bias in the identifications.

In the identification of jet stream clouds, no rigid requirements were imposed on their appearance before they could be associated with the jet stream. The literature indicates a wide range of cloud forms may exist; therefore, a liberal interpretation of what constituted jet stream cirrus in the satellite photographs was considered paramount if the definitive characteristics were to be determined. To further this objective the authors worked independently of one another in identifying jet streams from the satellite pictures.

Location of the jet stream relative to the cloud feature was necessarily more stringent. Whereas the form or general appearance of the high-level clouds was important, it was not sufficient in itself to locate the jet stream. There was a requirement for the clouds to be in a consistent position relative to the jet stream axis. There had to be some limit or line in the cloud pattern that defined the axis. Even though the literature is not entirely consistent, there is general agreement that high-level clouds related to the jet stream should favor the tropical side and end abruptly in the vicinity of the axis. This general configuration was made a requirement for locating the jet stream in this investigation. Actually some investigations indicate the jet should be somewhat poleward of the cloud edge, i.e. in the clear air. A separation of 30 to 50 n. mi. is typical according to Conover [3] and

Kadlec [9] in cases of extensive cirrus sheets, but Conover also mentions that a separation of even 200 n. mi. or more may occur, especially in cases of banded cirrus. Because these distances are within the normal range of inaccuracy in locating the jet stream, the authors felt little would be gained by making so fine a distinction. Therefore, the jet streams were located on base maps exactly at the cloud edge shown in the pictures. Furthermore, this procedure made a more objective technique for the geographical positioning of the identified features. To be more objective, it was thought that the conventional analysis should be performed by someone other than the authors. The operational maximum wind analyses of the U.S. Weather Bureau's National Meteorological Center (NMC) were chosen for this purpose.

When the jet stream analysis of the pictures was completed, the positions were transferred as line segments to the conventional analysis nearest in time for comparison.

The rules governing the verification required that the picture position (1) be within 200 mi. of the NMC position, (2) be essentially parallel to the NMC position (i.e. making an angle of no more than 15 deg.), and (3) be considered incorrect if it switched from one NMC jet stream to another, even if the first two rules were satisfied.

It was hoped that the first two rules would minimize the number of cases showing discrepancies because of time differences, data errors, analysis ambiguities, picture-gridding errors, and the aforementioned possibility of separation between cloud edge and jet stream. Regarding rule 3, Oliver et al. [14] and Kadlec [9] show the cirrus edge switching from one jet axis to another when two jet streams are in close proximity. However, since this test was to determine whether a given cloud image defines a given jet stream, obviously an image that throughout its length defines more than one jet stream position could not be considered correct.

4. RESULTS OF PRELIMINARY EVALUATION

It was immediately obvious that not all NMC jet streams within the pictures were detected; this was expected, but it was not the objective here. The question was: when clouds of the appropriate character appear, do they correctly identify the jet stream? Averaged among the three authors, 41 percent of the jet stream positions selected from the pictures were verified by the NMC positions. Among the three individuals involved the picture positions ranged from 38 percent to 48 percent correct. The total number of picture locations selected ranged from 58 to 117. The individual selecting the fewest cases had the highest percentage correct: the one selecting the most had the lowest percentage correct. This obviously indicates a difference of opinion as to the cloud structure defining the jet stream. In any case, the preliminary results were rather poor.

All cloud features were then categorized in order to determine which cloud structure was the most reliable. There were six categories in all. Category A (fig. 1a) comprises any extensive layers of "mostly covered" clouds that ends abruptly along a smooth edge. This edge is sometimes enhanced by its shadow and/or by transverse banding embedded in the edge of the cloud layer. All cases of narrow bands (15 mi. or less in width) are in Category B (fig. 1b). Examples of streaks appear in Category C (fig. 1c) and include cases of either a single streak or intermittent streaks, as opposed to striations, in a cloud layer. Category D (fig. 1d) is composed of patchy clouds showing organization along a line. Category E is limited to those cases that are very questionable as jet cirrus or those cases of subtle cloud features. Those cloud features taken under poor viewing conditions, such as oblique views, poor lighting, etc., are classified as Category F. No examples of the last two categories are shown since they are largely self-explanatory.

Classification of cases into these categories was necessarily subjective. Many cases were readily classified, but not all. Indeed, overlap was sometimes indicated. Nevertheless, the summary of the verification in table 1, individually and collectively by category, suggests some meaningful results.

Clearly, the cloud character of Category A was the most reliable. The percentage verification averaged among the authors was 62 percent. Unanimity among the three authors was prominent here. Individual verification percentages varied only from 58 to 66 percent. Of the cloud features identified among the authors, nearly two-thirds were identical.

Results of the verification in Categories B–F were very poor. Every category except one had a lower verification percentage than the over-all average of 41 percent correct. Verification was not only collectively poor among the three authors, but individually poor in these categories. These results, and the inconsistency among the authors in the number of cases selected, demonstrate that cloud characteristics within the categories B–F are not reliable indicators of the jet stream in TIROS photographs.

It was noted too that the reliability of narrow bands (Category B), streaks (Category C), or patches in a line (Category D) was considerably worse than of features in Category A and little more encouraging than the reliability of the vague cloud features in Category E. Although narrow bands and streaks may be clearly seen by observers within the earth's atmosphere, these same features may not be seen clearly by the satellite. The resolution of the TIROS cameras is at best about three miles, so that the cloud detail seen by the earthbound observer is superior to that seen from the space platform. Streaks tend to be rather thin. Thin cirrus is frequently not observed by the TIROS cameras, so that the farthest poleward limit of cirrus streaks may be difficult to discern, especially with underlying cloud layers, ice, or snow cover.

Even though the limitations of TIROS may have reduced the number of cases verified under Categories B, C, and D, the implication that these cloud characteristics are not reliable may be realistic. There is some

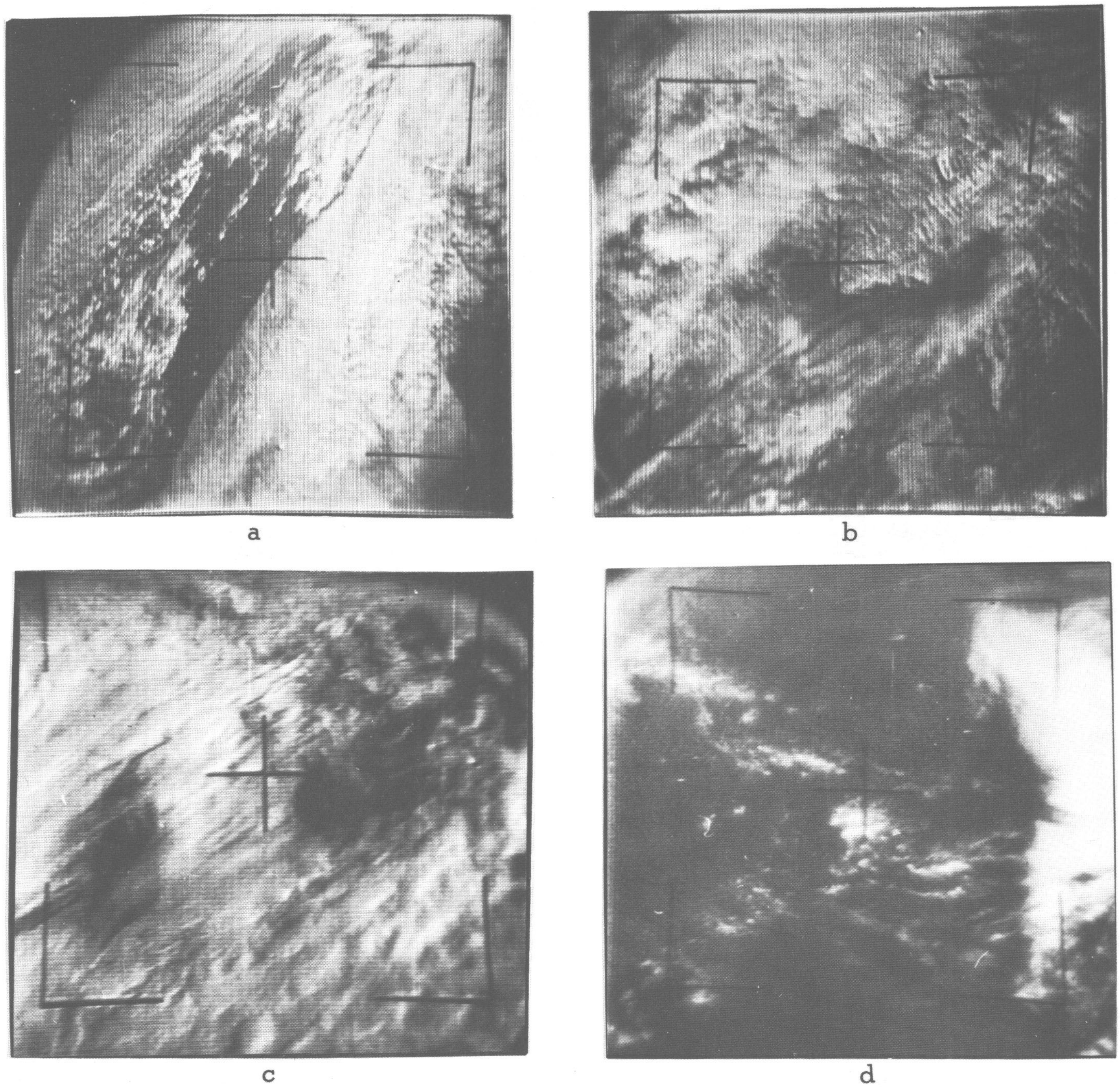


FIGURE 1.—(a) TIROS V photograph, pass 2569, direct mode, December 15, 1962, 1756 GMT. Note that the feature extending through the center of the picture is an abrupt edge of a cloud shield defined by a dark line or shadow band with a hint of transverse banding. This is an excellent example of Category A cloud features described in the text. North is approximately toward the top in all four pictures of this figure. (b) TIROS VI photograph, pass 1072, direct mode, November 30, 1962, 2108 GMT. The narrow band extending from the lower left toward the center of the picture is an example of Category B cloud features. (c) TIROS V photograph, pass 2223, direct mode, November 21, 1962, 1414 GMT. This is an example of cloud features within Category C. Note that a boundary to the streaked area at the north (top) is difficult to discern. (d) TIROS VI photograph, pass 1100, direct mode, December 2, 1962, 1916 GMT. The patches of cloud extending from the upper left through center into the cloud spiral at the right make this an example of Category D in which patches of cloud form a line.

doubt about using streaks or bands to locate precisely jet streams even by visual observations. In Conover's study, it was concluded that cirrus bands and streaks were within 200 n. mi. of the jet stream on the warm side only 50 percent of the time. The streaks and bands in this study appeared in areas of strong upper-level winds also, but they simply did not accurately locate the jet stream axis itself.

In Category F (pictures taken under poor viewing conditions) the verification was about as expected. Pic-

TABLE 1.—*Verification of cloud features in locating jet streams*

Category	Analyst 1		Analyst 2		Analyst 3		Combined	
	Right/Wrong	% Correct	Right/Wrong	% Correct	Right/Wrong	% Correct	Right/Wrong	% Correct
A	21/11	66	20/12	62	18/13	58	58/37	62
B	2/4	33	1/2	33	2/3	40	5/9	36
C	6/15	29	2/7	22	1/8	11	9/30	23
D	4/11	27	1/1	50	2/3	40	7/15	32
E	7/18	28	3/6	33	1/6	14	11/30	27
F	5/13	28	1/2	33	4/8	33	10/23	30
Total	45/72	38	28/30	48	28/41	41	100/144	41

tures taken at large oblique angles or under poor light should be used very cautiously, if at all, for any cloud interpretation purpose.

5. RESULTS OF FURTHER INVESTIGATION

Even though the 62 percent verification within Category A was far better than in any other, it was still too low to conclude that these clouds were effective in locating the jet stream. Some of the very best examples of cloud features were classified as incorrect in locating the jet. Most of these features were in the vicinity of jet streams, but for one reason or another failed to verify. Similar cases other than those in the primary study also came to light. Further study of such cases seemed required before one could conclude that jet streams cannot be reliably located using satellite pictures.

Several explanations for the low verification were discovered. One problem involved ambiguities in the analysis. Another was mistaking fronts for jet streams. A third involved cloud features of jet character formed by processes other than fronts or jet streams.

ERRORS RELATED TO ANALYSIS AMBIGUITIES

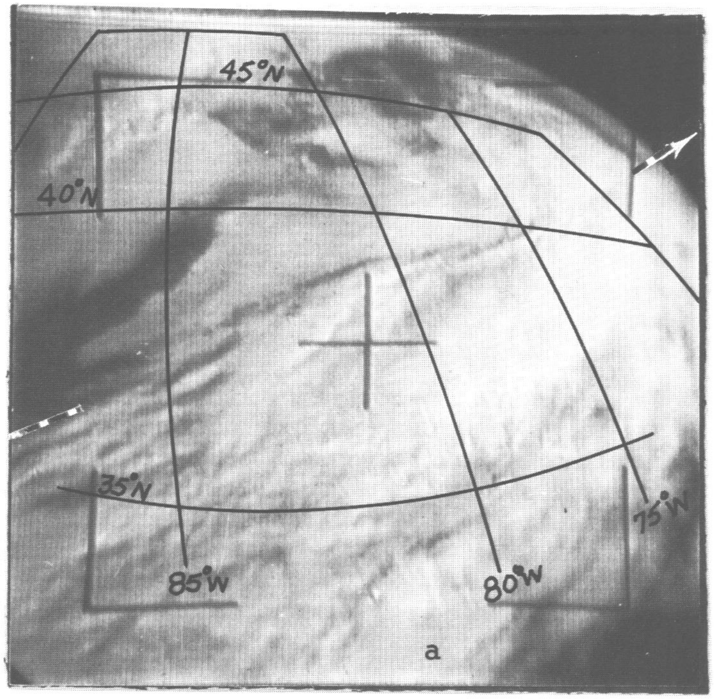
One of the problems was the variation in procedures used in jet stream analysis or, more precisely, it was the definition of the jet stream. The problem stemmed from the third verification rule, i.e., the identified feature must not shift or switch from one operational jet stream axis to another. When "switch cases" occurred, the operational jet stream positions were parallel or converged to become parallel and were usually within about 300 n. mi. of each other. In this one respect the model of Kadlec [9], and the examples shown by Oliver et al. [14] require clarification. Whereas the cloud distribution they presented did bear a general relationship to the jet stream, the relationship was imprecise since more than one analyzed jet stream was defined by the same cloud edge.

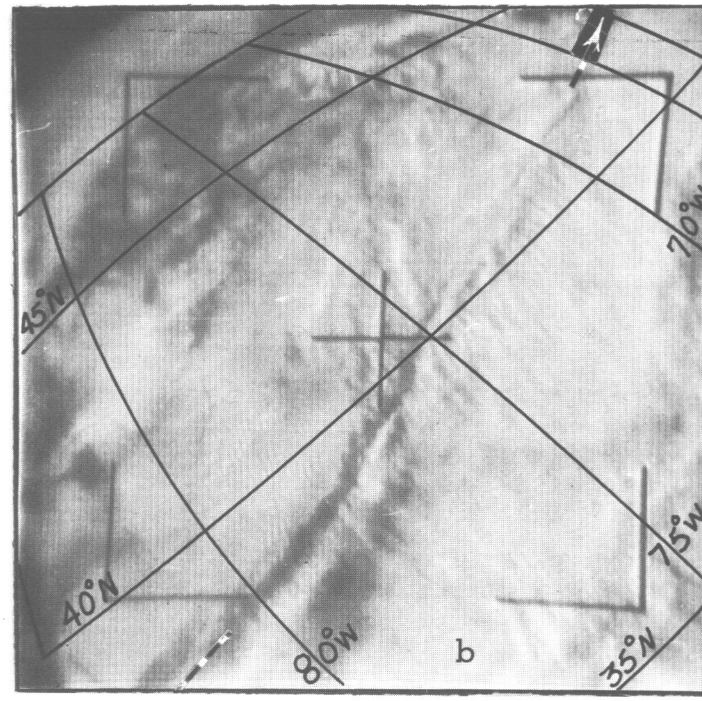
Figure 2 is an example. The cloud layer appears in the southern half of the picture and a dark line or shadow band outlines the cloud edge. Transverse banding also is visible in figure 2b. An analysis of the 250-mb. data nearest to these picture times is presented in figure 2c. Dark shading shows the cloud position. The cloud edge lies along the heavy solid line representing the axis of the isotach maximum. Since the dashed lines represent the original NMC analysis, it is clear that the pictured feature violated the third verification rule. However, as the revision shows, the axis of a single elongated isotach maximum lying along or very near the cloud edge is equally supported by the wind speed data.

The difference in the analyses is related to data limitations and the consequent operational definition of a jet stream. The NMC analysis techniques [20] establish as an important procedure that the jet streams conform to contour channels unless the observations clearly show otherwise. The established techniques for wind observations sometimes obscure the ageostrophic components, and in high wind situations these observations are often terminated below jet level. The revised jet stream analysis in figure 2c permits the axis of strongest winds to cross contours at small angles toward lower pressure. A cross-contour component toward low pressure should be expected in an accelerating current, and toward high pressures in a decelerating current. Many examples of cross-contour flow, particularly in jet maxima, are found in the literature. For instance, Murray and Daniels [13] found transverse flow directed to the left in the entrance area of a jet maxima and to the right in the exit area, attributing this to ageostrophic motions. Riehl [18], in an analysis over the central United States, permitted the jet stream to cross over a contour interval of 800 ft. toward lower pressure in the entrance region of the jet maximum.

These findings along with analyses at other constant pressure levels and vertical cross sections (not shown) suggest that a single primary jet stream occurred east of the trough as shown in the revised analysis in figure 2c. The axis was placed very near Nashville and Huntington (open wind barbs) because these stations had abbreviated wind data presumably because of high winds. The wind observation at Huntington terminated more than a kilometer below the 250-mb. level at 145 kt. The northwesterly jet weakened so much in the trough region that it could not be distinguished from the southwesterly jet stream. Only a single primary jet could be distinguished in cross sections made in the eastern United States. An ill-defined secondary branch could be identified through southern Virginia, but clearly (in fig. 2c) the primary jet extended from Texas to New England.

A similar situation involving a jet stream cloud pattern





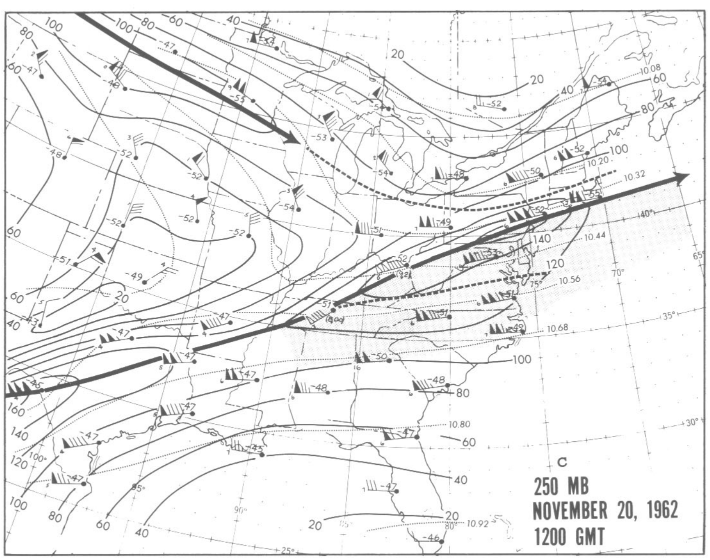
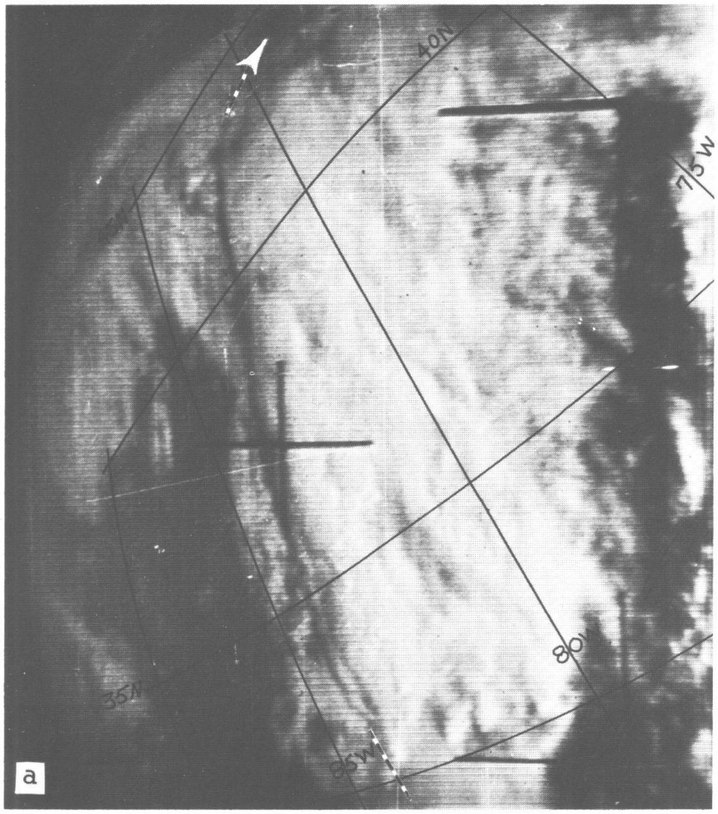


FIGURE 2.—(a) TIROS V photograph, pass 2209, direct mode, November 20, 1962, 1447 GMT. A well defined jet stream cloud characteristic is shown by the abrupt cloud edge and marked by a dashed line at either end. The edge is outlined by the shadow extending roughly through the center of the picture from left to right. The cloud shield lies south of that line so that the jet stream should be directed from southwest to northeast. (b) TIROS VI photograph, pass 922, direct mode, November 20, 1962, 1358 GMT. This picture showing an area centered a bit northeast of figure 2a, is of the same jet stream cloud. Transverse banding is visible in this photograph, but not in 2a. (c) 250-mb. analysis, November 20, 1962, 1200 GMT. The heavy solid lines represent jet stream positions; thin solid lines, isotachs in knots; fine dotted lines, height contours in tens of kilometers; dashed lines, the NMC jet stream positions that depart from this analysis. Temperatures are given in degrees Celsius. The wind speeds and directions are shown with the usual symbols. The two stations showing open 50-kt. wind barbs are Nashville, Tenn. and Huntington, W. Va. reading from southwest to northeast. These stations suffered abbreviated wind observations that terminated below the 250-mb. level, but the last reported wind is shown together with the height in parentheses. The cloud shield shown in parts a and b is represented here by the shaded area.

and also shown by Oliver et al. [14] occurred on October 4, 1962 (fig. 3). The position of the jet stream indicated by the clouds would have been classified incorrect in the verification scheme. The jet stream feature in figure 3a lies between 80° and 85° W., and exhibits an abrupt smooth cloud edge, with well defined shadow. Also, the cloud texture to the east is different from that to the west. Figure 3b depicts the 250-mb. wind analysis. The dashed lines show the NMC operational jet stream positions whereas the heavy solid lines show the revised positions or axes of the isotach maximums. In the original comparison with NMC positions, the cloud edge switched at a small angle across the contours from the southernmost to the northernmost jet positions in the eastern portion of the trough. In the revised analysis, the position of the cloud edge is in close agreement with the single axis of the isotach maximum. As in the previous case, the operational positions conform closely to contour channels whereas the revised position of the isotach maximum axis makes a small angle with the contours—crossing toward lower pressure in the area of acceleration.

From a further theoretical point of view, it appears unlikely that a cloud layer and its well defined edge should actually cross uninterrupted and undistorted such a sig-



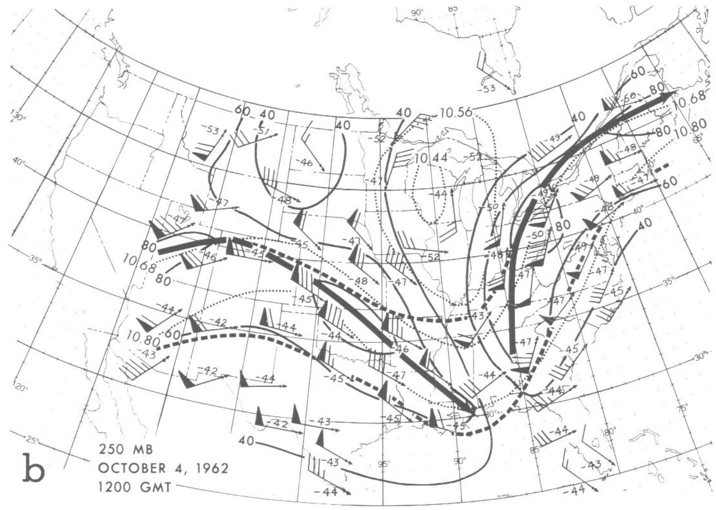


FIGURE 3.—(a) TIROS V photograph, pass 1534, direct mode, October 4, 1962, 1311 GMT. The jet stream is identified by the cloud shield, to the right of center, terminating abruptly along the dark shadow band at the center. The edge is identified by a dashed line at either end. (b) 250-mb. analysis, October 4, 1962, 1200 GMT. All lines and symbols have the same meaning as in figure 2c.

nificant feature of the wind field as the jet stream. The axis of the jet itself represents an abrupt boundary between cyclonic and anticyclonic shears with the consequent abrupt changes in the vertical motion across the boundary just as shown in the Riehl et al. [19] model. This suggests that the unaltered extension of a cloud mass, and particularly the abrupt edge across this boundary, is not to be expected. It seems more reasonable to expect the well defined cloud edge to coincide with the abrupt change in vertical motion. Since the revised analysis is compatible with theory, the data, and previous observational studies, the conclusion that the jet axis (isotach maximum axis) defines the cloud edge seems justified.

If this conclusion is correct then it resolves much of the ambiguity in the analysis possibilities, indicating that the satellite photographs of these cloud features would supplement existing data and aid analysis even in areas relatively rich with upper-air data. Also the cloud features should be especially useful where strong wind itself forces termination of wind observations even before jet level is reached.

Over the period studied there were collectively nine cases in Category A in which cloud edges switched from one operational jet position to another. These discrepancies involved the same problem discussed in the two cases above. In all nine cases, reanalysis of the maximum wind axis position was feasible and supported by the data so as to bring about agreement with the cloud edge position. With the reanalysis of these nine cases, the percentage of Category A cases that verified was improved from 62 to 72 percent.

ERRORS DUE TO FRONTAL CLOUDS

The problem here lay in confusing frontal cloud bands with jet stream clouds. Frontal cloudiness occasionally covers an extensive area that ends abruptly as a long smooth trailing edge. Further, a jet usually is found to the rear but in the vicinity of the frontal zone, and when cirrus is not detected or is less prominent than frontal cloudiness, the rear edge of the frontal band may be interpreted as the jet stream. Among the Category A cases this error was committed 13 times collectively among the three analysts. An example of such a case is shown in figure 4a. The rather broad band running through the center of the picture bears most characteristics of jet stream cirrus. Further, the layer appears striated suggesting the presence of cirrus. Nevertheless, these clouds appear to occur in conjunction with the frontal cloud band that agrees with the position of the front rather than that of the jet stream.

In figure 4b the abrupt rear edge of the frontal clouds and its shadow led to a mistaken identification of the jet stream, whereas in reality the less prominent cloud features behind the frontal cloud sheet were associated with a splitting jet stream. Surface observations verified that these cloud sheets were cirriform. Both end abruptly in

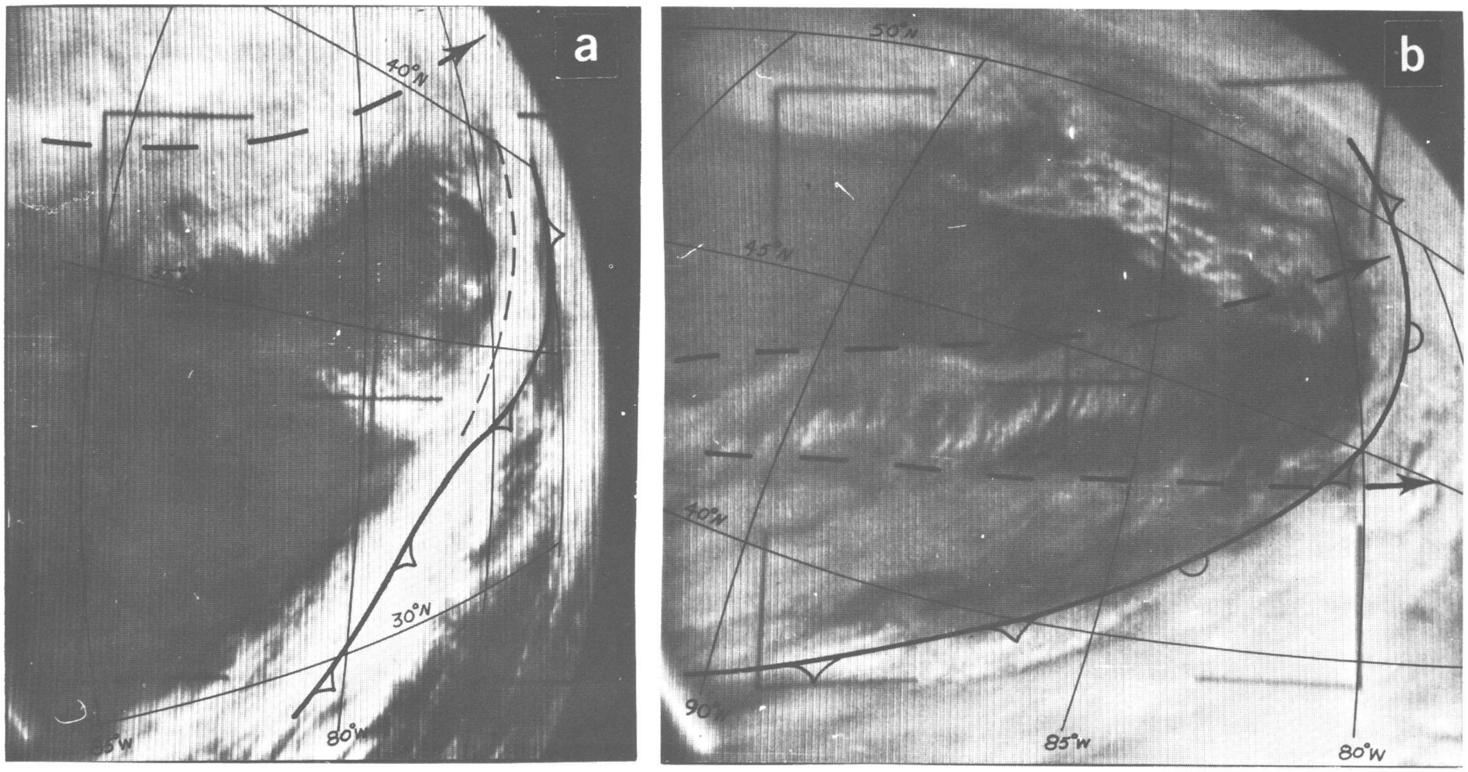


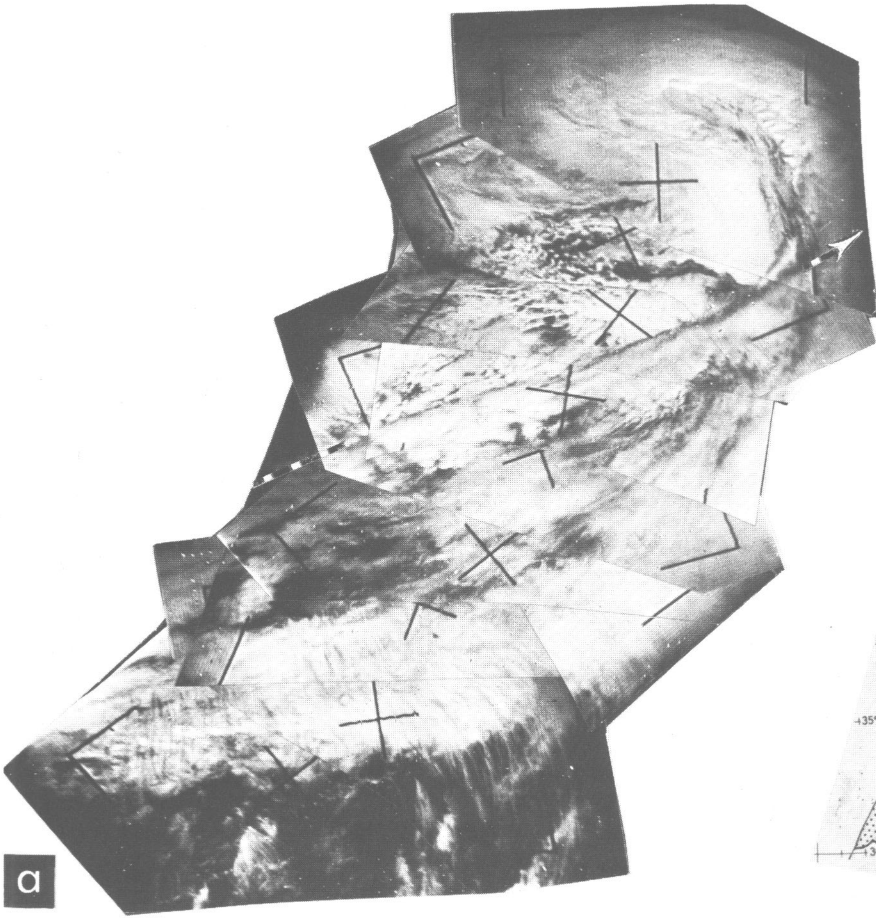
FIGURE 4.—(a) TIROS VI photograph, pass 1917, direct mode, January 27, 1963, 1720 GMT. Positions of the surface cold front and trough are shown with conventional symbols except they are left open to obscure as few data as possible. Jet stream positions are shown by dashed lines. (b) TIROS VI photograph, pass 937, direct mode, November 21, 1962, 1440 GMT.

the immediate vicinity of the jet streams. One irregularity worthy of note is the horizontal undulation of unusually large amplitude in the cloud edge next to the northernmost jet stream. Note that the southernmost jet stream and associated cloud pattern intersect the frontal position at a sharp angle near the point of occlusion. Evidence that the cloud pattern extends over the frontal clouds can be seen in other photographs of this situation.

The question is: Can these misplacements be prevented? Is there any way to distinguish between jet stream clouds and other clouds of similar appearance? The evidence suggests the answer is frequently yes. Frontal cloud bands, particularly their rear edges, usually show cyclonic curvature that becomes more pronounced near the accompanying cyclone, tending to spiral inward toward the cyclone center. There was no evidence in this study of a jet stream cloud spiraling into a cyclone center. Jet stream cloud edges on the other hand more often are either comparatively straight or show anti-cyclonic curvature. Cyclonic curvature of the jet stream cloud edge may occur, but from this study and previous experience it is rare, and it is not as pronounced as that of a frontal band. Characteristic cloud patterns may not ordinarily form with pronounced cyclonic curvature of the jet stream. Cyclonic curvature tends to neutralize the divergence patterns on the tropical side of the jet stream in straight flow [1]; conversely, anticyclonic curvature tends to enhance them.

Jet stream clouds, as opposed to frontal cloud bands, usually do not appear as broad bands of nearly uniform width. Characteristic differences between the two are demonstrated in figure 5. The bright cloud band (fig. 5a) associated with the front curves cyclonically northward into the cloud spiral associated with the cyclone. Clouds of jet stream origin overlie the southern portion of the front extending some distance over the cold air at the surface. The cloud edge identifying the jet stream is nearly straight. Whereas the jet stream is related to the front, it does not precisely parallel the front but approaches and finally crosses the front, presumably near the point of occlusion, just as was shown above in figure 4b. Because of the sparsity of surface data the apex of the warm sector could not be established with great certainty. However, since an occlusion is indicated from continuity, and since well-defined cloud spirals are associated with cold cyclones in middle latitudes, the jet stream would be expected south of the cyclone and poleward of the cold front, but intersecting the frontal clouds somewhere near the beginning of the occluded front. This particular model is sometimes quite useful in identifying jet stream clouds.

It seems reasonable to expect that frontal clouds and



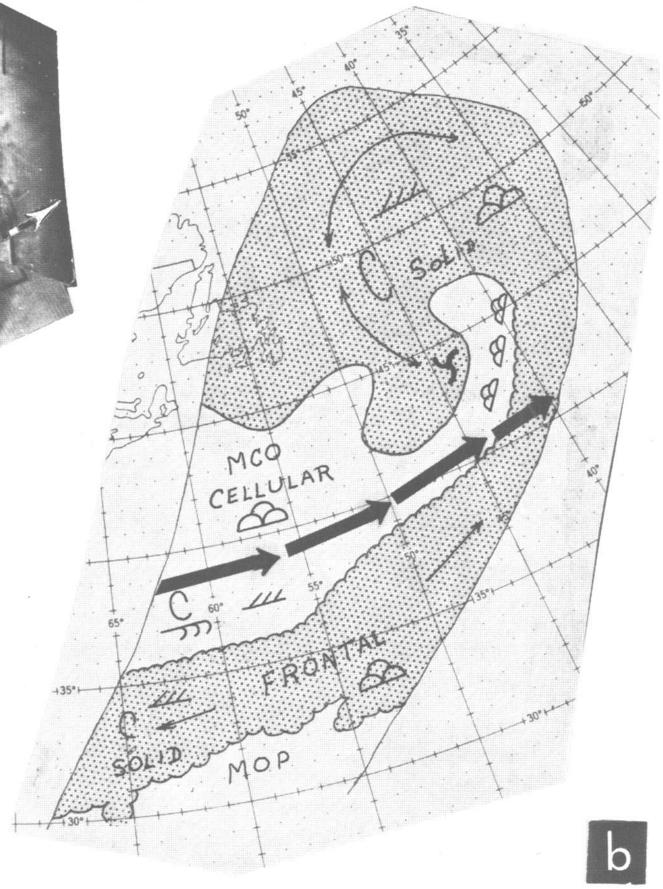
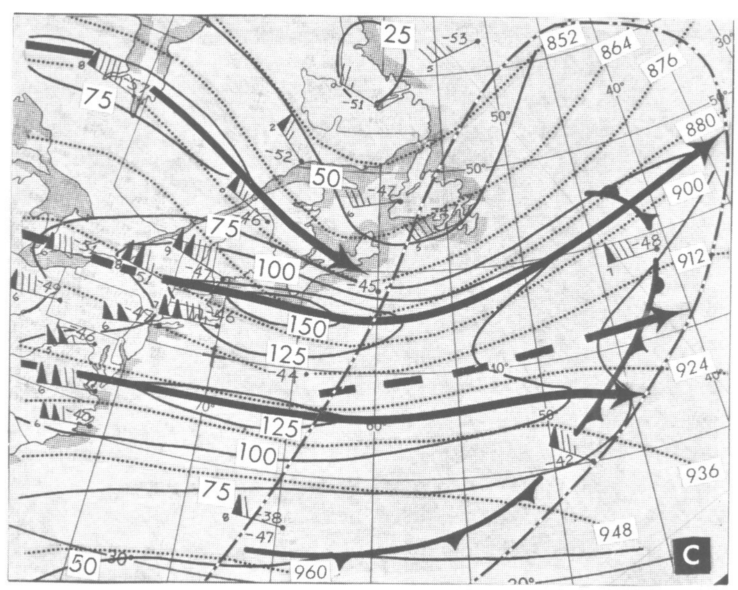


FIGURE 5.—(a) Mosaic of TIROS VII pictures, pass 3006, tape mode, January 8, 1964, 1627 GMT. The jet stream clouds define a sharp line about one-third of the way down from the top of the mosaic. A dashed line appears at either end of the cloud edge. The cloud spiral of a vortex is shown at the top and a frontal band below center. (b) Nephanalysis of mosaic showing the location of the principal features. The heavy arrows show the jet stream position. MCO means mostly covered with clouds; C, covered with clouds; and MOP, mostly open. The symbols for stratiform, cirroform; and cumuliform used on operational nephanalyses also appear. (c) 300-mb. analysis, January 8, 1964, 1200 GMT. The NMC jet stream positions are shown by heavy solid lines, the position determined from the picture mosaic by dashed lines. Within the nephanalysis area the surface frontal positions are indicated. All other lines and symbols have the same meaning as in figure 2c.



jet stream clouds can be distinguished from one another. At least any cloud aggregate of jet stream character but showing cyclonic curvature, should be used only with great caution to locate the jet stream. In practice, reference to current synoptic analyses, which was not permitted in this study, usually will help delineate the frontal cloudiness. If the 13 frontal cases in Category A of this study were eliminated, the verification would be improved to 83 percent correct.

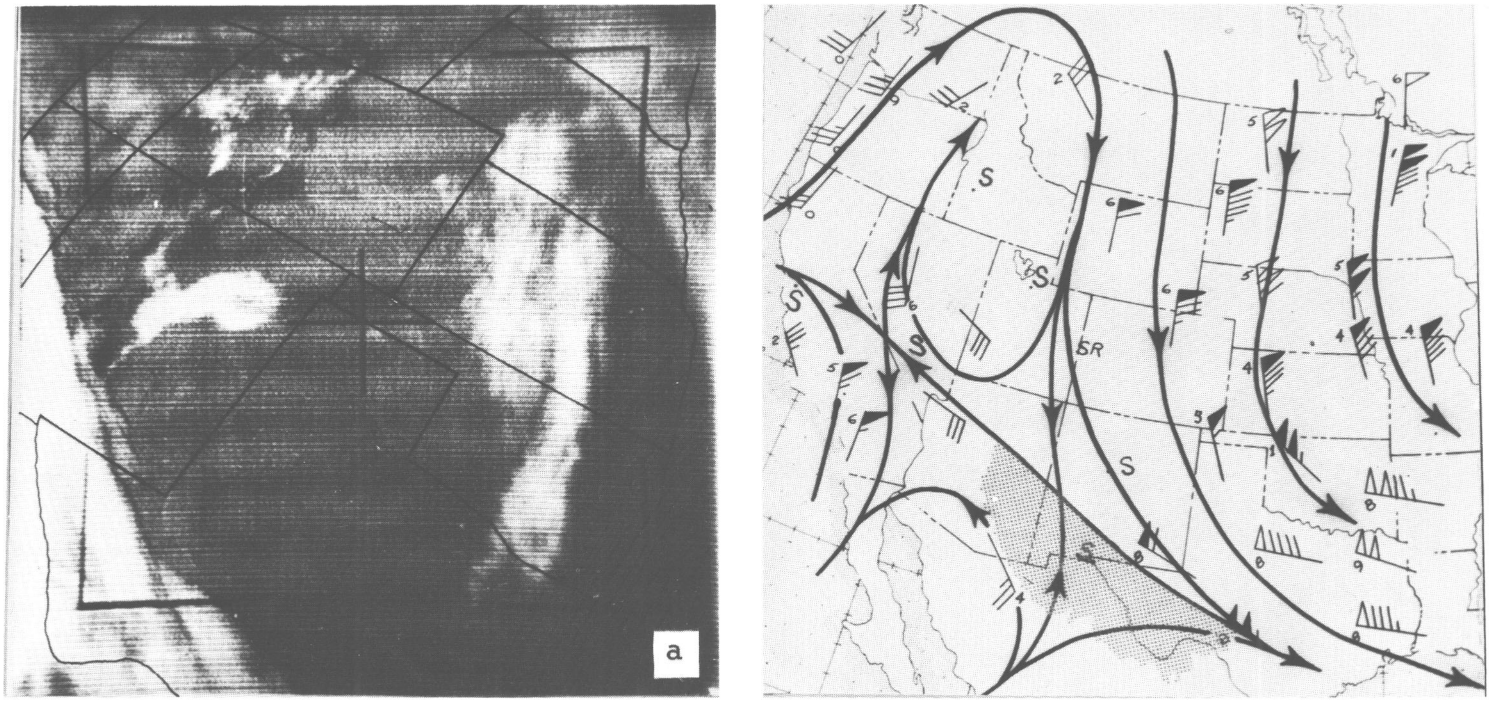


FIGURE 6.—(a) TIROS V photograph, pass 2526, direct mode, December 12, 1962, 1759 GMT. Jet stream cloud characteristics complete with shadow that were associated with the col shown in figure 6b. (b) Streamline analysis of maximum wind level December 12, 1962, 1200 GMT. Wind directions and speeds are plotted as usual. Open 50-kt. barbs indicate the stations where wind observations terminated below the level of maximum wind. The maximum wind level for this area was almost entirely within the 10- to 12-km. layer. The symbol S represents locations of wind too slow to determine the maximum speed. Shading represents jet stream cloud location in figure 6a.

OTHER ERRORS

Unfortunately, smooth abrupt cloud edges are also formed by processes other than those associated with jet streams and fronts. Consequently they can lead to improper location of the jet stream. The remaining 14 cases of misidentification in Category A were such cases, but they could not be resolved as were those discussed in the two previous subsections. Paradoxically, most of these were cases of cloud features aligned with very weak winds along the convergence asymptote through a col area. Figure 6 is an example of this situation. The abrupt cloud edge extended uninterruptedly across highly mountainous terrain in Arizona and New Mexico and finally into the plains area of Texas before it was related to strong winds. This col condition persisted and was identified as a jet stream by all three authors for three consecutive days in the Southwest causing a collective total of nine errors in jet stream location. No characteristics were discerned that would enable one to distinguish these clouds from bona fide jet clouds; therefore, in a situation of this type the use of pictures alone in jet stream analysis can cause serious error. Whether or not high altitude cols frequently produce such well defined cloud patterns cannot be determined without much additional evidence.

The remaining 5 of 14 cases of misidentification were divided among two other meteorological situations. One was the case in which the abrupt cloud edge was created by upslope motion on the east side of the Rocky Mountains. The other situation was one in which the clouds of jet stream character appear to have been associated with an upper trough line. It is the experience of those involved in this study that high-level cloud shields ending abruptly at the trough line are rare. In these rare instances, the suspicion is that the cloud edge departs from the trough line to define the jet stream.

These 14 cases could not be resolved. In the final verification of the 82 collective cases appearing within Category A, 14 were incorrect and 68 correct in identifying the jet stream. The 68 cases were divided among 31 different picture features. Comparison of these features with the meteorological situations provided several other interesting indications. All 31 features occurred in the immediate vicinity of jet stream maxima. Most were restricted to the area of acceleration and of course to the right of the jet stream and therefore to the divergent zone in the model of Riehl, et al. [19]. In five instances the clouds did extend some distance downstream into the area of deceleration. Only three features occurred with jet streams having winds weaker than 100 kt. The great majority, 25, occurred with winds in excess of 120 kt. All but four features occurred with jet streams from the southwesterly quadrant.

6. SUMMARY AND CONCLUSIONS

Certain high level cloud features in satellite photographs can be used to identify and accurately locate the jet stream. The primary and most indicative characteristics are an extensive cloud shield or a "mostly covered" cloud layer ending abruptly along an edge that extends over a long distance, is rather smooth, and shows no rapid changes in curvature just as suggested by Kadlec and Oliver et al. The cloud layer should lie within the anticyclonic wind shear area (the tropical side of the jet stream) so that the jet stream is defined by the abrupt polar edge of the cloud layer.

Usually the cloud layer has a decidedly different texture and brightness than the lower clouds. Identification of the cloud edge is materially aided whenever a shadow band is cast on lower layers and/or by the appearance of transverse banding. A shadow band not only outlines the cloud edge but also indicates the cloud level is high and thus is more likely to be related to the jet stream. The indications are that these characteristics will correctly locate jet streams better than 80 percent of the time, with the provisions that (1) the jet stream is defined as the axis of the isotach maximum which does not necessarily conform strictly to contour channels, and (2) the jet stream clouds can be distinguished from frontal clouds.

It also appears that the pictures can be a valuable supplement to conventional observations not only in sparse data areas but even in dense data areas. As a consequence of provision (1) above, it was shown that jet stream characteristics in satellite photographs may sometimes lead to the analysis of a single primary jet stream where multiple jets adhering to contour channels might otherwise have been analyzed. Further, a position obtained from satellite data is quite useful in the stronger jet stream situations since under these conditions at least one and often several stations in the vicinity of the jet stream usually experience "short runs" (wind observations terminating at low levels).

Not only should one expect to distinguish frontal from jet stream clouds, but the frontal clouds themselves are often an aid in identifying or lending credence to clouds of jet stream character. Figure 5 in fact is a model picture of the position of jet stream clouds relative to spiral patterns, cold fronts, and occluded fronts.

Narrow cloud bands a few miles in width, streaks, and patches of clouds oriented in lines generally should not be used to identify jet streams. Whereas clouds of this character do occur with the jet stream, they are not accurate indicators on the TIROS picture scale. Oblique views and views under twilight conditions should be used rarely if ever in jet stream identification. The problem of oblique views is becoming minimized with the advent of vertically viewing satellites.

The evidence shows that the jet stream cloud shield is not only found only on the tropical side of the jet stream but also definitely favors the entrance area of the maximum there, just as is shown by a portion of the model proposed by Riehl et al. [19]. There are exceptions to this model. Extension of the cloud shield into the exit area on the tropical side of the jet stream does occur. This requires further study, as does the absence of substantial cloudiness on the polar side of the jet stream in the exit area. In the first instance, clouds upon passing into the exit area after formation in the entrance region may at times be slow in dissipating even if descent is occurring. The dissipation may be retarded by descent that is slow relative to the heat required to sublimate the ice particles—the heat requirement being greater than that in an evaporation process. In the second case, the absence of clouds on the polar side of the exit area might be attributed to inadequate moisture to reveal the upward motion theoretically present there.

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NEW WEATHER BUREAU PUBLICATION

Technical Paper No. 54, "Meteorological Summaries Pertinent to Atmospheric Transport and Dispersion Over Southern California," G. A. DeMarrais, G. C. Holtzworth, and C. R. Hosler, 1965. For sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Price, $1.25.

For the southern California area south of 34.5° N. information is presented on the wind regime, both surface and aloft, temperature gradients and inversions, precipitation, and synoptic regimes. These summaries, in map and tabular form, give an indication of the manner in which effluents move from one place to another and of the capacity of the atmosphere in this region to reduce the concentration of effluents emitted into it. The data were originally intended for preliminary use in selecting nuclear reactor sites, but some may be used to evaluate community air pollution problems. The function of each of the summarized meteorological elements in the transport and dispersion of effluents is briefly explained.